Prolonged Effects of Severe Drought on Oak Radial Growth in Eastern North America

An Honors Thesis (HONR 499)

by

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Abstract

Climate change is expected to increase drought events that can lead to mortality of oak trees, an important economic and ecological group. This study evaluated the duration in years of oak tree decline after severe droughts by comparing the post drought annual ring width to the average ring width in the five-year period before the drought in 116 sites across eastern North America. The duration of recovery was broken into three groups, based on if recovery from the drought was immediate (0-3 years), protracted (5-10 years), or improbable recovery (over 10 years). The percentage of trees at each site in each recovery class was compared across four sub-regions in eastern North America to evaluate differences across the range of oak species. Improbable recovery was significantly lower in the north-east part of the distribution than the north-west or south-west. Improbable recovery was significantly higher for the western distribution than the eastern. These results suggest that oaks in the west are more likely to be weakened or injured by a drought and susceptible to other stresses, such as disease or insect attack.

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Process Analysis

The research I engaged in was mainly data analysis on tree growth and drought that allowed me to become very familiar with Microsoft Excel and Minitab. I had 153 species x site increment core collections from an established database to transform before I could begin my analysis. Most trees within each site had two cores, which needed to be averaged together. If a singular tree had more two cores, then I had to use a correlation function to find the two that were most strongly correlated before averaging. After that, I had to pair climate data from another data base with the site's core increment data, allowing me to mark the start, duration, and end of the major drought at that site. I used an average of the ring widths for the five years prior to the drought as a basis for if the tree was growing at its previous rate after the drought. To do this, I had to use an "if" function within Excel to count the years it took for the tree to return to its prior growth rate. I summed how long it took each tree to return to this previous growth rate within the site. Then, for every site, I used a "count if" function to place the number of trees into their appropriate decline duration classes. Because the sites had different numbers of trees in them, I had to convert this count into a percentage. To be able to evaluate spatial relationships, I needed to use the "if" function to separate each site into one of four sub-regions based on latitude and longitude. Then, I had to use Minitab to check the assumptions of an ANOVA test, which my data did not fit. So, I had to run a non-parametric Kruskall-Wallis test instead. This process took me a lot longer than I was expecting it to, but it did allow me to get familiar with all of the idiosyncrasies and many of the functions in Excel and Minitab.

After doing all of the analytical work, I needed to immerse myself in the literature to be able to make logical inferences based on my results. I must have read over sixty peer-reviewed scientific articles on tree decline and drought. Some of which I did not end up incorporated into my final paper, mainly because a different paper explained the same concept better or I had a similar paper that focused on the eastern United States or oak trees. Reading the papers and finding useful information was not at all an issue; however, sometimes it was difficult to remember which articles had what information in them. Towards the end of my writing, I was trying to find a better way to organize what each article discussed in relevance to my thesis. I felt like there had to be a more efficient way than what I was doing, and I had just found a bunch of new articles to read through and incorporate into my thesis. I did not get to try out a lot of different methods, but I found that highlighting and scrolling through the articles was more effective for me than copying the same relevant information into a Word document to outline the information in the way I thought I would use it. This came as a surprise to me, as the latter sounds like a more efficient way of organizing information. I cannot seem to be able to reconcile why highlighting and scrolling through the articles was a smoother method for me to write my thesis.

One of my biggest stressors occurred when I realized that my formula for my sub-regions had not worked correctly and it had placed too many sites into the southeast sub-regions, skewing my statistics. I had to re-run my statistics, which actually lead to different results than I had originally made inferences on. Of course, this occurred while I was editing a poster to present my thesis at a conference later that week, so it caused a lot of panic and stress until the statistics were fixed. Then, I could go back through the literature to verify anything I had already written was still valid and to find additional support for my conclusions based on the new results.

Fortunately, the error was caught before the poster was finished and taken to the Indiana Academy of Science conference, where I got to communicate with professionals about my research. Later, I presented the same poster at the Ball State University Student Symposium, which was another good way to gain experience presenting in a professional setting. This was also a good opportunity for me to network with professionals which could potentially help my future career.

These were the first professional meetings I got to attend, and I am thankful to my advisor for convincing me to present at them. I was very skeptical about going when he originally brought up the idea. I do not consider myself a strong public speaker, so it was a good environment to practice speaking in front of a group, since I was mainly talking to one or two individuals at a time. These meetings were also just a great learning experience outside of my own personal practice with public speaking. I got to attend a lot of small presentations at the Indiana Academy of Science meeting to learn what people are studying and learning about in our field right now. Additionally, I got to interact with other professionals and gain some experience in networking, especially with people who were interested in my poster and who asked me questions on my project.

Despite all the great experience that I gained, the biggest challenge I had was giving myself due dates for getting parts of my thesis done. I have found that I need inflexible due dates to work effectively. I never thought that I needed true due dates before this project, but I discovered that self-imposed due dates are too flexible and easy to move to accommodate other responsibilities. Because it was not due right away, it seemed like it could be moved further down the list of priorities. Even though, it definitely needed done when I had originally decided to finish that section. I had a heavy semester in the fall and I had some health complications that made it too easy to continue to push back working on my thesis to the point that I did not finish it during the semester that I had signed up for my thesis credits. The following semester when my advisor posed a weekly meeting, my thesis moved along way more efficiently. Then, I needed to have whatever part I was working on at the time actually done and turned in to him. Although it was extremely frustrating to learn this fact about myself, I am glad that I now know that I cannot finish long term projects with self-imposed due dates or, if there are no inflexible due dates, that I will have be extremely conscious and careful about pushing back flexible due dates. This is extremely important to know about myself to be able to work on it now and in the near future.

Introduction

Drought occurs globally, affecting human and natural systems (Ficklin et al. 2015, Dai 2011). Droughts are one of the most expensive natural disasters, with annual US losses of $6 – 8 billion (Andreadis and Lettenmaier 2006, Dai 2011, Easterling et al. 2007). Severe drought events can greatly affect agriculture, water resources, ecosystems, basic human welfare, and local economics (Dai 2011, Michaelian et al. 2011). Additionally, major drought episodes have been documented to cause vegetation mortality on every continent and most biomes (McDowell et al. 2011, Michaelian et al. 2011, Peng et al. 2011).

McDowell et al. (2008) suggested three hypotheses of mechanisms for drought related mortality: 1) biotic agent demographics, 2) hydraulic-failure, and 3) carbon starvation. Biotic agent demographics suggests that drought affects pests or pathogens, allowing them to become better mortality agents. Hydraulic failure suggests that lowered amounts of soil water couple with high evaporative demand will cause xylem to become air filled and be unable to transport water. The plant tissues will dehydrate, eventually leading to cellular death. Carbon starvation suggests that stomatal closure in the attempt to prevent hydraulic failure will cause reduced carbon gains from photosynthesis, causing plant starvation from the continued need of carbohydrates to maintain metabolism.

Because drought is defined as a dry period relative to its normal condition, drought can even affect wet and humid regions (Dai 2011, Easterling et al. 2007). Areas that are increasing in precipitation can still be affected by droughts if the precipitation events are less frequent, but heavier, leading to longer dry spells (Andreadis and Lettenmaier 2006). Similarly, arid areas, like the southwest, are more prone to drought due to low and infrequent precipitation (Dai 2011), which is intensified by the higher temperatures in this region (Groisman et al. 2004, Andreadis and Lettenmaier 2006, Karl et al. 2008).

Droughts are described by their intensity, duration, and spatial coverage (Dai 2011). Intensity can be described as the deficient amount of precipitation, soil moisture, or water storage relative to evaporative demand (Dai 2011) and can be exacerbated by high temperatures, high winds, low cloud cover, or low humidity (Karl et al. 2008). Previous intense droughts, such as the one from 1772 to 1775, have been documented to cause tree mortality and alter forest structure over large geographic ranges in eastern North America (Pederson et al. 2014). The droughts of the 1930s and 1950s were the most severe of the twentieth century due to their long duration and large spatial extent, covering almost all of the conterminous United States (Andreadis et al. 2005). During the multi-year and seasonal droughts of the 1980s-2000's, decline and mortality of oaks, mainly in the red oak group, have been reported in the eastern United States, spanning from Missouri to South Carolina (Allen et al. 2010). Another study in Missouri found oaks from the red oak group exhibiting significantly lower growth rates for ten years following drought events in the 1930's and 1950's (Dwyer et al. 1995). These lower growth rates after a drought event have been found to lead to oak mortality (Pedersen 1998). Mortality rates of red oaks in the Ozarks from the 2005-2006 drought have been documented at over 60%, with peak mortality rates occurring two to three years after the drought event (Fan et al. 2012).

The wide effect of droughts on trees and forests provides concern for the possible effects of climate change (Allen et al. 2010, Teskey et al. 2014). Drought trends are changing over the contiguous United States, but they are not similar between all regions. Drought in the western United States is becoming more prevalent and severe, while drought in the northeast United states is becoming less prevalent (Andreadis and Lettenmaier 2006, Easterling et al. 2007, Ficklin et al. 2015).

The Palmer Drought Severity Index (PDSI) is the most widely used drought index for long term characterization (Andreadis et al. 2005). PDSI uses precipitation and surface air temperature, to account for evapotranspiration and soil moisture conditions (Dai et al. 2004, Dai 2011, Andreadis et al. 2005). While PDSI is a measure of meteorological drought (Dai et al. 2004, Dai 2011), it is related to hydrological and agricultural drought by its consideration of evapotranspiration and soil moisture (Andreadis et al. 2005).

The objective of this study was to identify oak responses to drought across the eastern United States. Variation in decline durations of oak trees can be compared to major differences in climate across this large geographic range. With this variation in climate, regions that are pre-disposed to long recoveries from drought can be identified.

Methods

Two increment core were obtained from a minimum of 10 oak trees at each of 116 sites across the eastern United States (Figure 1). Due to the geographic extent of this analysis, pre-existing data was used from a variety of sources from diverse sites across the eastern United

States as described in LeBlanc and Terrell (2009, 2011) and LeBlanc and Stahle (2015). If there was more than one oak species sampled at a site, then cores were taken from at least 10 trees per species, giving a total of 153 species x site increment core collections. Annual tree-rings were crossdated to assign each ring to the year it formed (Holmes et al. 1986). Ring widths were measure to 0.01 mm precision. Ring width chronologies for the two cores sampled for each tree were averaged by year.

For each tree, the ring-width values for the five years prior to the drought event at each site were averaged. Starting at the first year after the end of the drought, each tree-ring was compared to the pre-drought width for that tree to determine how many years it took for the tree to recover, with ring-width equal to or greater than its pre-drought value. Each tree in a site was categorized based on its growth decline duration: 0-3 years, 4-10 years, or over 10 years. Because the number of trees at each site was not constant, the actual number of trees in each decline duration was converted into a percentage for every site.

Palmer Drought Severity Index (PDSI) data for every study site was obtained from the National Climate Data Center (Andreadis et al. 2005). The worst drought between 1950 and 1980 was identified based on both severity (large negative PDSI values) and duration (years). This time period was selected so that the oaks would be mature canopy trees with essentially stable radial growth. The most severe droughts were identified to be in either the mid-1950's or mid-1960's for all study sites. Other studies have also documented severe regional droughts in the eastern United States during these periods (Andreadis et al. 2005, Ficklin et al. 2015)

To evaluate spatial variation in decline duration across the eastern United States, the sites were split into four sub-regions. The center point of the study region was the location 37.7N latitude x -88.0W longitude, near the three state border of Illinois, Indiana, and Kentucky. This point was used to define the northeast, northwest, southeast, and southwest sub-regions. The southeast was not analyzed due to low sample size. Because the data for percentage of trees in the tree decline classes violated the normality assumption for an ANOVA test, and there were an unequal number of sites distributed throughout the four sub-regions, a Kruskall-Wallis test was used to compare the median percentages of trees in each decline duration class among the sub-regions. Two-sample t-tests were used to compare the mean percentage of trees with decline durations of over ten years between north versus south and between east versus west sub-regions.

Results

Median percentage of trees that recovered shortly after the drought ended (decline durations of 0-3 years) varied among the three sub-regions ($p = 0.025$), and was higher in the northeast than in the northwest (Figure 1). Median percentage of trees with protracted recovery after the drought ended (decline durations of 4-10 years) did not significantly vary among the three sub-regions. Median percentage of trees not expected to recover after the drought ended (decline durations over 10 years) differed among the three sub-regions ($p = 0.002$), and was lower in the northeast than in both the northwest or southwest (Figure 2, Figure 3). For decline duration over ten years, no difference was found between the mean percentages between the north and south sub-regions; however, the mean percentage for the west sub-region was higher than the east sub-region ($p < 0.001$, Figure 2).

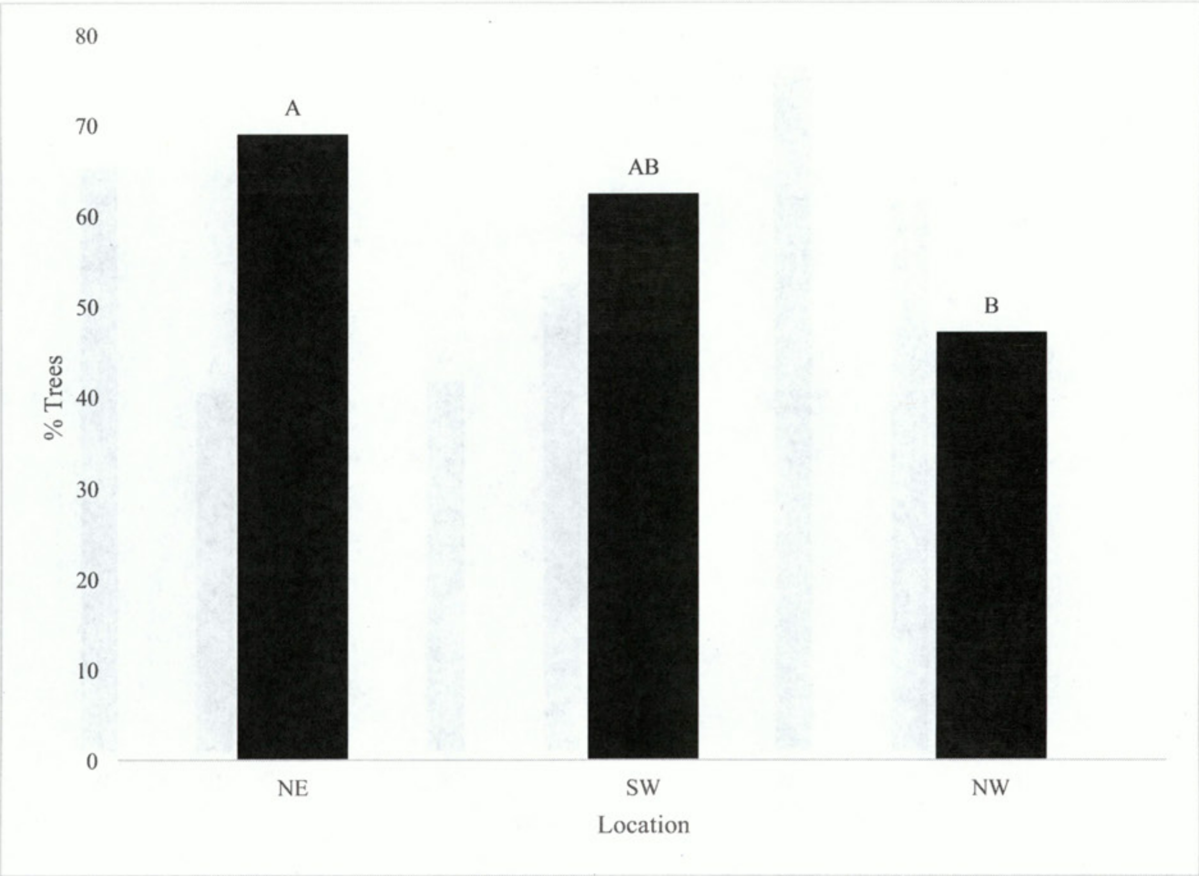

Figure 1. Median percentage of trees that recovered shortly after the drought ended (decline durations of 0-3 years) in the eastern US was compared among sub-regions using a Kruskal-Wallis test. Different letters above the bars represent a significant difference between sub-regions. If bars share a letter, there is no difference between the sub-regions.

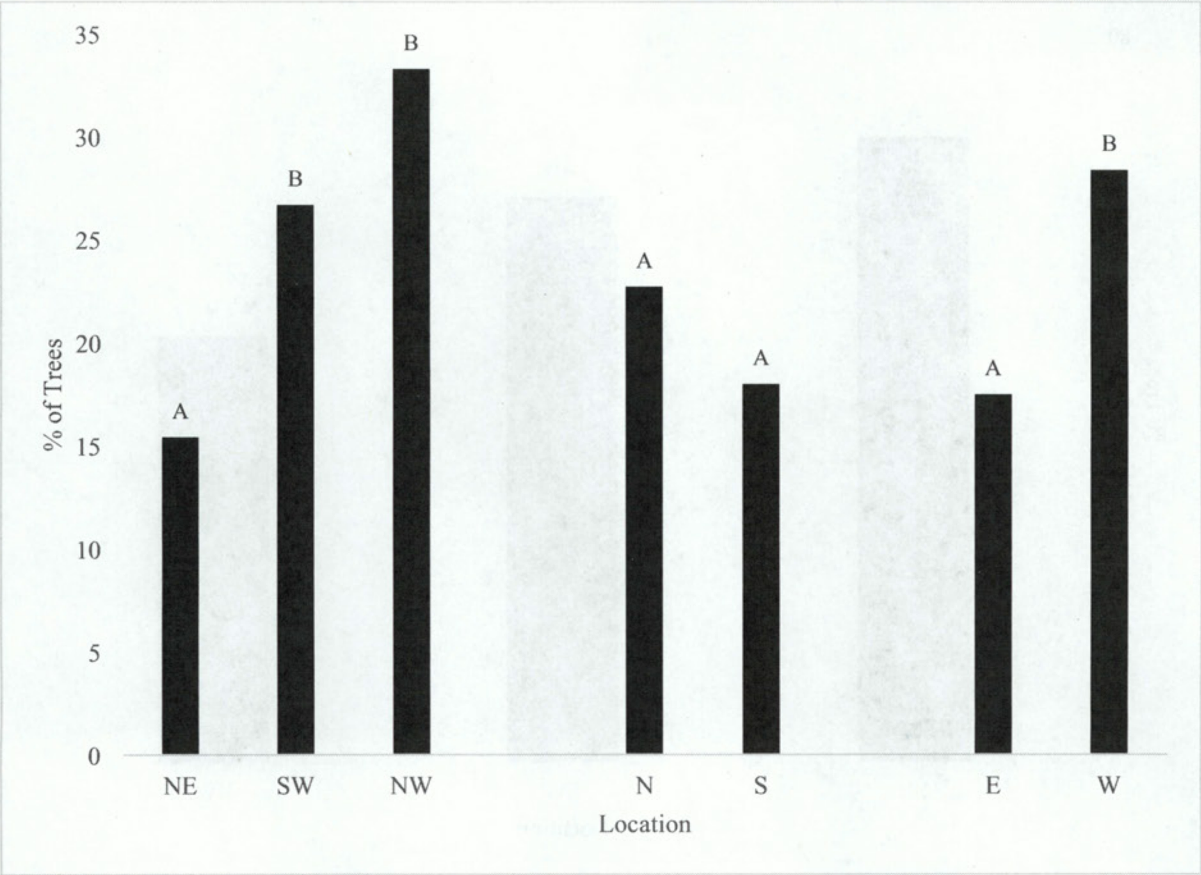

Figure 2. Percentage of trees with decline durations of over 10 years in various sub-regions in the eastern US. A Kruskal-Wallis test was used to compare median percentage of trees between the NE, SW, and NW sub-regions. A two-sample t-test was used to compare mean percentage of trees between the N to S and the E to W. Different letters above the bars represent a significant difference between sub-regions. If bars share a letter, there is no difference between the sub-regions.

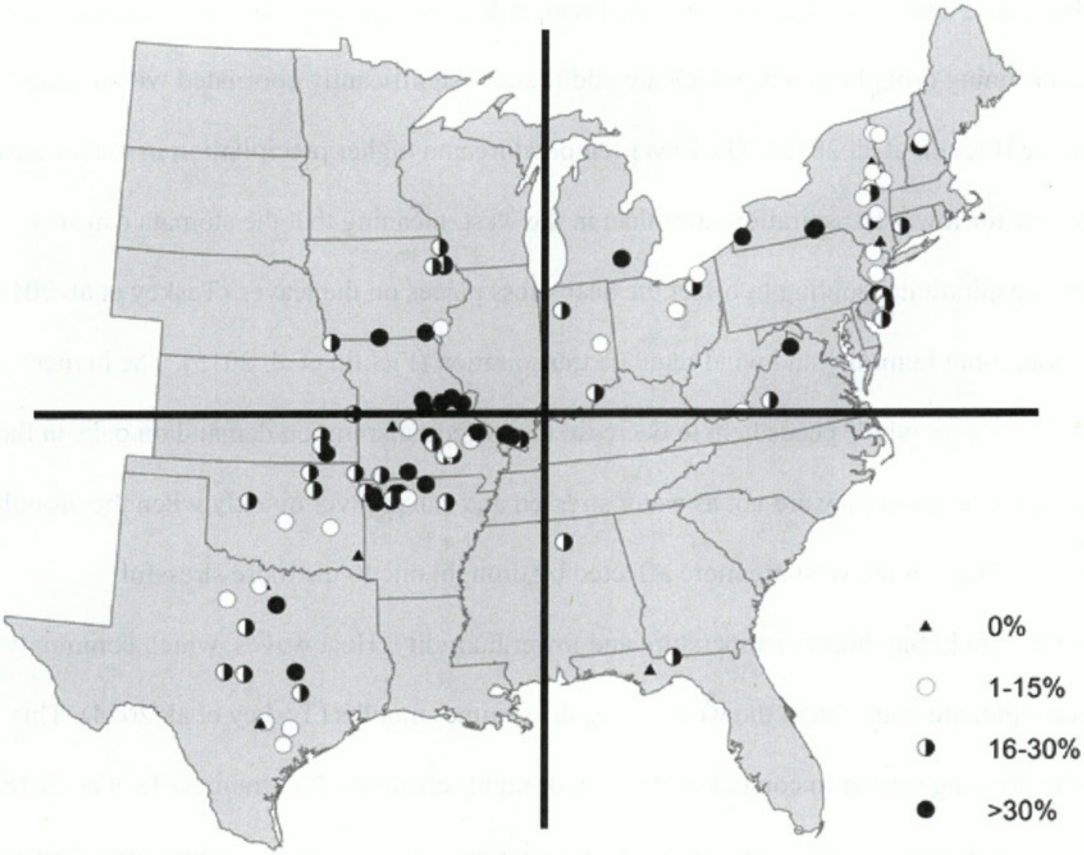

Figure 3. Map showing the median percentage of trees with decline durations of over 10 years in each site across the four sub-regions. The center point for the four sub-regions is 37.7N x -88.0W, near the three state border of Kentucky, Indiana, and Illinois.

Discussion

Trees in the northeast having a higher median percentage of trees that recovered shortly after the drought end and having a lower median percentage of trees that are not expected to recover after the drought reflects a less stressful environment than the northwest or southwest. Similarly, a higher mean percentage of trees not expected to recover in the west than in the east reflects that the west has a more stressful climate that hinders drought stress recovery. Oaks in the northeast are less affected by drought due to the lower temperature, higher precipitation, higher humidity, and decreased wind speeds. Precipitation is the most important climatic variable when determining drought trends, which are additionally significantly correlated with average air temperature (Ficklin et. al 2015). The lower temperature and higher precipitation in the northeast region allow for lower transpiration rates than in the west, meaning that the stomata can stay open for transpirational cooling to offset the heat stress places on the leaves (Teskey et al. 2014.) Furthermore, both humidity and wind regulate transpiration (Ficklin et al. 2015). The higher humidity and lower wind speeds help to decrease the evapotranspiration demand on oaks in the northeast, meaning that they are not as water stressed and can recover quickly when the drought event ceases. Oaks in the west are more affected by drought due to the more stressful environment, including higher temperature and lower humidity. Heat waves, which commonly lead to drought, are common in the west during the summer months (Teskey et al. 2014). This causes the growing season to coincide with peak drought sensitivity (D'Orangeville et al. 2018). Warmer summer temperatures can cause greater vapor pressure deficit and evaporative demand, resulting in greater evapotranspiration and decreased availability of soil water (Diffenbaugh and Ashfaq 2010, LeBlanc and Terrell 2009, Martin-Benito and Pederson 2015, Mishra et al. 2010, Teskey et al. 2014, Williams et al. 2013). This moisture stress causes longer decline durations of oaks in the west.

Decline duration reflects the trees' resilience, defined as the ability of a system or organism to return to its previous state after a disturbance (Duveneck and Scheller 2015, Lucash et al. 2017). Resilience is affected by predisposing stresses, which weaken the trees, and inciting stresses, which cause damage to the trees (Manion 1981). Oaks in the northeast are more resilient and recover quickly after a drought event, because they are not under a predisposing, stressed environment; however, oaks in the west are less resilient and predisposed by their long-term, stressful environment to go into decline from the inciting drought event.

Stressed trees have decreased wood production that indicates reduced carbon allocation to lower priority uses, including starch storage, chemical defenses, and even xylem production (LeBlanc et al. 1992, LeBlanc and Stahle 2015). Instead, trees must allocate large amounts of carbon to maintenance (Teskey et al. 2014). This reallocation lowers resilience and increases the chance of hydraulic failure (LeBlanc and Stahle 2015) and susceptibility to contributing factors, such as pests or pathogens (LeBlanc 1992, LeBlanc et al. 1992, Manion 1981, Pedersen 1998). Not only is tree susceptibility to pests increased by drought stress, but insect outbreaks have been found to increase during and after drought due to the warm summer temperatures and decreased precipitation (Berg et al. 2006, Raffa et al. 2008), because the same abiotic stressors that are the driving forces for drought are also important driving forces for insect outbreaks (Sturrock 2012). These contributing factors slow tree recovery, causing longer decline durations where there are pest outbreaks.

Climate change will greatly impact mature oak tree responses to drought. Climate change has been shown to lower tree resilience (Duveneck and Scheller 2015), with the greatest effect occurring in scenarios with the highest mean annual temperature (Lucash et al. 2017). However, increases in precipitation can nullify increases in drought from higher air temperatures (Easterling et al. 2007). Precipitation in the northeast is increasing due to the high humidity and increased water vapor content in the air, which increasing under green-house gas induced climate change (Ficklin et al. 2015, Martin-Benito and Pederson 2015). Conversely, precipitation in the west is decreasing (Ficklin et al. 2015), predisposing these trees to any drought stress from rising temperatures (Martin-Benito and Pederson 2015).

Many climate change models are projecting increases in drought frequency, with rainfall occurring in fewer, more intense events separated by longer dry periods, causing increased stress (Iverson et al. 2017, Swanston et al. 2018). With many trees functioning at their hydraulic limits, any increase in moisture stress could be cause for increased decline (Pederson et al. 2014). Furthermore, longer dry periods are problematic as tree recovery after drought stress has been documented to cease after the occurrence of another drought, even decades after the first event (Dwyer et al. 1995, McDowell et al. 2008, Pedersen 1998).

Additionally, climate change is increasing the effect of insects as a contributing factor to tree decline. Insects have a high physiological sensitivity to climate and high mobility. The rising temperatures allow for increased growth, short generation times, and high reproductive rates (Weed et al. 2013, Dukes et al. 2009, McDowell et al. 2008). Climate change also improves overwinter survival and increases transmission rates (Dukes et al. 2009, McDowell et al. 2008). These effects can allow insects to increase enough in abundance to be able to infect healthy, non-stressed tress (Weed et al. 2013). Thus, insect outbreaks become more frequent as climate change exacerbates abiotic stressors, such as drought (Sturrock 2012, Williams et al. 2013).

In conclusion, trees in the northeast were less negatively affected by drought, whereas trees in the west were more negatively affected. Trees in the west inhabit a predisposing, hot and dry, stressful environment, which allows the drought event to incite more damage, lowering resilience and increasing susceptibility to insect attack. Through the effects of climate change, the west is predicted to be a more stressful environment with more drought events. Similarly, climate change is allowing insects to become better disturbance agents and have a greater impact on tree health.

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